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Review

The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost Part I. Case study of Antarctica

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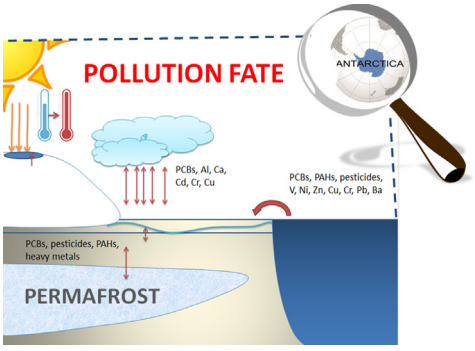
HIGHLIGHTS

- Permafrost distribution in Antarctica and reemission of pollutants
- Environmental fate of anthropogenic pollution remobilised from the cryosphere
- Pollution from permafrost present in the Antarctic affects the living organisms.

GRAPHICAL ABSTRACT


POLLUTION FATE
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PCBs, PAHs, pesticides, V, Ni, Zn, Cu, Cr, Pb, Ba
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ABSTRACT

This article presents a review of information related to the influence of potential permafrost degradation on the environmental fate of chemical species which are released and stored, classified as potential influence in future Antarctic environment. Considering all data regarding climate change prediction, this topic may prove important issue for the future state of the Antarctic environment. A detailed survey on soil and permafrost data permitted the assumption that this medium may constitute a sink for organic and inorganic pollution (especially for persistent organic pollution, POPs, and heavy metals). The analysis of the environmental fate and potential consequences of the presence of pollutants for the existence of the Antarctic fauna leads to a conclusion that they may cause numerous negative effects (e.g. Endocrine disruptions, DNA damage, cancerogenicity). In the case of temperature increase and enhanced remobilisation processes, this effect may be even stronger, and may disturb natural balance in the environment. Therefore, regular research on the environmental fate of pollution is required, especially in terms of processes of remobilisation from the permafrost reserves.

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1. Introduction

Permafrost, defined as soil, rock, or sediment that remains at or below 0 °C for two or more consecutive years, covers vast areas (Bockheim et al., 2013). Permafrost is most extensive in the Arctic, but also exists on the Central Asian Plateau and in ice-free areas of Antarctica, including the Antarctic Peninsula region (Bockheim et al., 2013). An impermeable barrier associated with permafrost prevents drainage and leads to the occurrence of high water table wetlands, lakes, and ponds (Vincent et al., 2011). Moreover, it affects the biogeochemistry and geomorphology of the landscape, and thereby biological productivity and biodiversity, especially in polar regions (Vincent et al., 2011; Dobiński, 2012; Chaves et al., 2017; Almeida et al., 2014, 2017; Correia et al., 2017).

Global climate changes and the related cryosphere degradation as the effects of temperature increase have been observed in both Northern and Southern Hemispheres over the last several decades (e.g. Serreze et al., 2000; Vaughan et al., 2003; ACIA, 2005; Turner et al., 2005; Mulvaney et al., 2012; IPCC, 2013; Kejna et al., 2013). Considering that permafrost underlines an area of 22 million km^2, processes related to the state and changes in permafrost concern a significant part of the global land area (approximately 17%) (Bockheim et al., 2013). Recent studies show that the periglacial zone is one of the most rapidly changing areas on earth (e.g. Cooper et al., 2011; López-Martínez et al., 2012; Karlsson et al., 2012, 2015; Oliva and Ruiz-Fernández, 2017; Ravanel et al., 2017; Oliva et al., 2018).

It should be emphasised that except for the relatively well known and thoroughly described influence of permafrost on water and soil chemistry in the internal region of the North America, Europe, and Asia (e.g., Carey, 2003; O'Donnell and Jones Jr., 2006; Petrone et al., 2006; Frey et al., 2007; McClelland et al., 2007; Frey and McClelland, 2009; Keller et al., 2010; Bagard et al., 2011; Douglas et al., 2013; Larouche et al., 2015; Manasypov et al., 2015; Szopińska et al., 2016; Lehmann-Konera et al., 2018), there is still little known about permafrost related geochemical processes and its role in shaping of the chemical status of areas recently uncovered by glaciers in the Antarctic and Arctic regions.

Research projects carried out in recent years resulted in numerous works regarding to the presence of permafrost in the Antarctica (e.g., Guglielmin and Cannone, 2012; López-Martínez et al., 2012; Bockheim et al., 2013; Guglielmin and Vieira, 2014; Guglielmin et al., 2014; Simas et al., 2015; Oliva and Ruiz-Fernández, 2017). Some papers pointed out that the ongoing trend of increasing air temperatures could affect soil organic matter (SOM) turnover and soil C-CO_2 emissions in the terrestrial ecosystems of Maritime Antarctica (Pires et al., 2017). Several studies prove that Antarctic seawater, snow, and presumably soils are becoming important secondary sources remobilising POPs (Cabrerizo et al., 2012, 2013; Klánová et al., 2008). They can also cause an increase in the concentration of legacy pollutants such as hexachlorobenzene and polychlorinated biphenyls (PCBs) in the Antarctic environment (Cabrerizo et al., 2013). A lot of international agreements have been passed to protect Antarctica. The Protocol on Environmental Protection to the Antarctic Treaty is the most notable of them. Since its implementation, importation of specific POPs has been prohibited, and also research stations and practices have been improved (Cabrerizo et al., 2012). Polycyclic Aromatic Hydrocarbons with a higher molecular weight, i.e. with 4–6 aromatic rings, are other contaminants highly toxic to organisms in the Antarctic environment. They have carcinogenic and mutagenic properties (Martins et al., 2010). Another group of pollutants which may be stored in permafrost and are hazardous to the environment consists of heavy metals. In the case permafrost-affected soils of Antarctica, it should be also emphasised that the freezing process may significantly influence the distribution of elements within the soil profile (Nagare et al., 2012).

Considering that inorganic and organic contaminants are temporarily stored in sediments and may be released into environment with the thawing and freezing of permafrost (e.g., Carey, 2003; O'Donnell and Jones Jr., 2006; Petrone et al., 2006; Frey et al., 2007; McClelland et al., 2007; Frey and McClelland, 2009; Keller et al., 2010; Bagard et al., 2011; Douglas et al., 2013; Larouche et al., 2015; Manasypov et al., 2015; Szopińska et al., 2016; Szumińska et al., 2018), this work presents an attempted comparison and summary of knowledge on potential influence of permafrost on the chemical status of the Antarctic ecosystem. Special attention was paid to sources of inorganic and organic compounds (natural or anthropogenic, local or long-distance) and their potential influence on Antarctic biota. The proposed summary could be important for understanding the potential environmental hazards associated with the accumulation of anthropogenic pollution in the Antarctic environment. Taking into consideration the holistic approach to the polar geomorphic system proposed by Dobiński (2012), we can assume that both processes – accumulation and release of contaminants - occur simultaneously, and contaminants are transferred continuously within the cryogenic environment.

2. Permafrost distribution in Antarctica

The map provided by Bockheim and Hall (2002) shows the ice-free area in Antarctica where permafrost can potentially occur, as well as the probable occurrence of subglacial permafrost (Fig. 1). Only 0.35%, or 45,000 km^2 of Antarctica is ice-free (Bockheim, 1995). Continuous permafrost occurs in continental Antarctica. Its thickness reaches 1000 m in the McMurdo Dry Valleys and 500 m on the Ross Island. In the Antarctic Peninsula permafrost is discontinuous, with a thickness ranging from 3 to 25 m on the Deception Island, 20–100 m on the King George Island, and 35–200 m on the Seymour Island (Bockheim et al., 2013). Detailed research on seasonal permafrost thawing shows

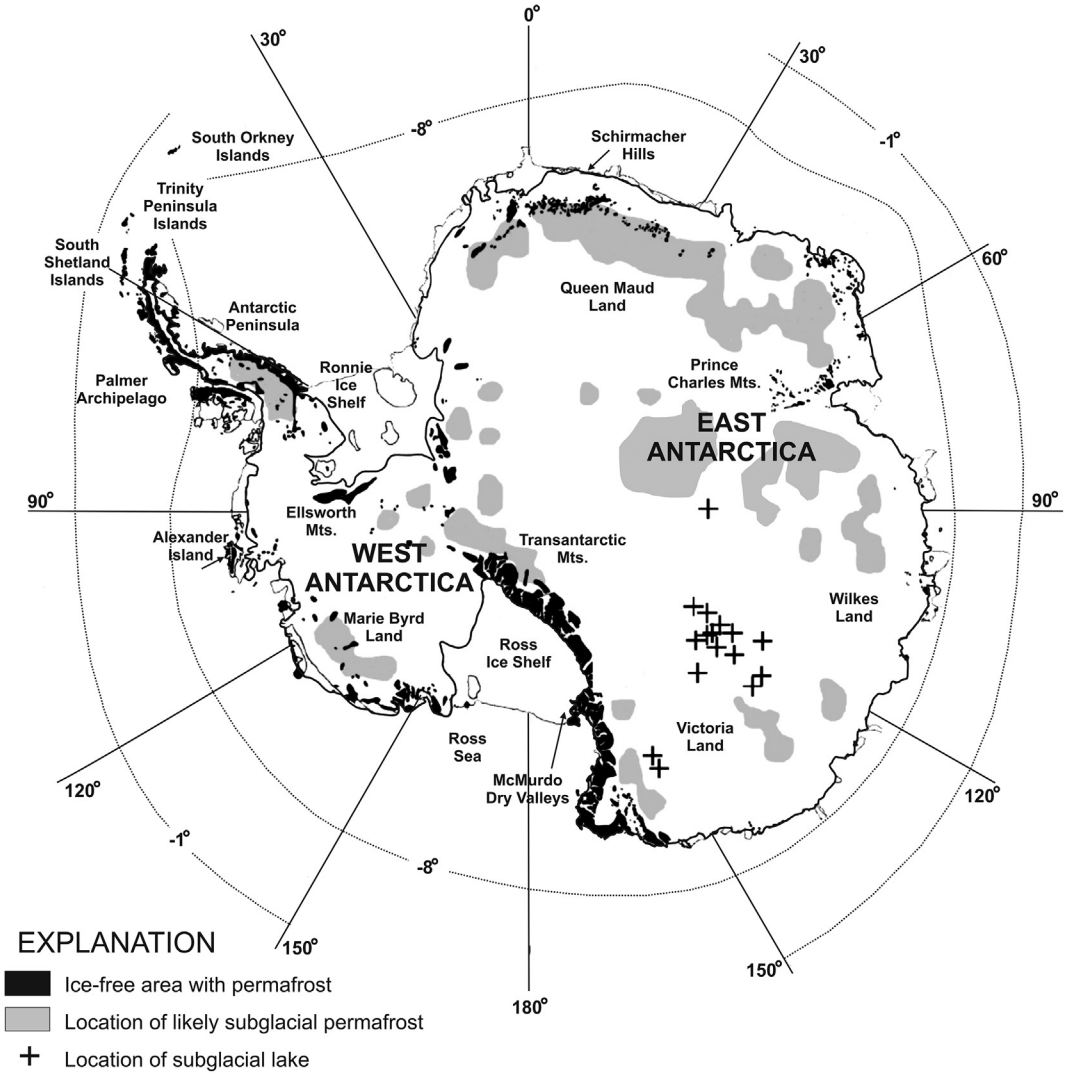


Fig. 1. Permafrost distribution in Antarctica (Bockheim and Hall, 2002). Ice-free areas are presented in black, probable distribution of subglacial permafrost beneath the Antarctic ice sheet is presented as shaded areas, subglacial lakes are depicted with a cross; The −8 °C and −1 °C mean annual air temperature isotherms are taken from Weyandt.

different depths of the active layer, varying from 0 to 60 cm in the Interior Antarctica (Bockheim, 1995; Bockheim and Hall, 2002) to prevailing ranges between 10 and 200 cm in the Antarctic Peninsula (Vieira et al., 2010), in particular cases exceeding 600 cm (Bockheim et al., 2013). Moreover, Bockheim and Hall (2002) pointed out that the concept of an active layer is less relevant in interior Antarctica, because much of the permafrost in interior Antarctica is 'dry' in contrast to the Antarctic Peninsula and its offshore islands, and to maritime East Antarctica, where mainly wet permafrost occurs.

The detailed research conducted on the Antarctic Peninsula suggests that permafrost distribution in this area is largely controlled by local factors, such as marine disturbance (Vieira et al., 2010), duration and thickness of snow (Oliva et al., 2017a; Ferreira et al., 2017), land relief (Oliva et al., 2017a), lithology (Hrbáček et al., 2017), and vegetation cover (Almeida et al., 2014). Lithological conditions influence among others the average depth of active layer thickness. This layer in the South Shetland Islands usually exceeds 100 cm in loamy soils (de Pablo et al., 2013; Schaefer et al., 2012; Oliva et al., 2017b). The deepest active layer (>300 cm) was observed in bedrock in the vicinity of Bellingshausen site, located in the western region of the King George Island (Hrbáček et al., 2018). The active layer is the thinnest on the Deception Island, located in the South Shetland Islands archipelago. It reached only 30–50 cm (Ramos et al., 2017). According to some authors, the ocean influence limited permafrost occurrence at the sea coast (Correia et al., 2017; Ferreira et al., 2017; Strzelecki et al., 2018). However, several papers indicate geomorphological formations and soils evidencing permafrost-related processes in the ice-free area at low altitudes, e.g. seasonal thawing-freezing affected soils (Simas et al., 2015), patterned grounds (Dąbski et al., 2017), and frost mouds, sorted circles and stripes (Oliva and Ruiz-Fernández, 2017). Bockheim (1995) summarised that periglacial features related to freezing and thawing processes occur in the Antarctic as: gelifluction features (lobes, terraces, and sheets); patterned ground features (sorted and non-sorted circles, sorted and non-sorted polygons and nets, sorted polygons and nets, sorted steps, sorted and non-sorted stripes); ground ice features (ice wedges, rand wedges, rock glaciers, pingos, thermokarst, ice-cored drift). Inactive periglacial features also occur in Atarctic, namely: ice-wedge casts, inactive patterned ground, inactive rock glacier, inactive solifluction features.

The last of the mentioned formations as well as glacier retreat constitute evidence of climate change observed over the recent decades on the Antarctic Peninsula (e.g., Vaughan et al., 2003; Cook et al., 2005; López-Martínez et al., 2012; Mulvaney et al., 2012; Bockheim et al., 2013; Chaves et al., 2017; Pętlicki et al., 2017; Hrbáček et al., 2018; Szopińska et al., 2018). Mean annual air temperature along the western Antarctic Peninsula increased by as much as 3.4 °C, and mid-winter temperature increased by 6.0 °C over the past 50 years, making the region one of the most affected by climate warming (Vaughan et al.,

2003; Turner et al., 2005). Permafrost degradation was reported on the Antarctic Peninsula, even to the point of its disappearance at sites near the Palmer station (64°77′S) (Bockheim et al., 2013). Permafrost was much colder (−3 °C) southwards, close to the Rothera research station (67°57′S) with an active layer ranging between 0.76 and 1.4 m (Guglielmin et al., 2014). Guglielmin and Vieira (2014) concluded that the active layer thickness is directly proportional to the mean summer air temperature, and inversely proportional to the maximum snow depth in autumn. Recent research has also shown much greater permafrost dynamics in the Antarctic environment, associated with the generally high dynamics of morphological processes in the area (Bockheim et al., 2013; Chaves et al., 2017; Almeida et al., 2014, 2017).

3. Environmental fate of anthropogenic pollution remobilised from the cryosphere

Recent decades have shown phases of the most rapid warming on the Antarctic Peninsula (Mulvaney et al., 2012; Bockheim et al., 2013). This raises a concern, especially in reference to potential changes in sea ice coverage and concurrent increase in anthropogenic emissions of contaminants from the southern hemisphere (Bargagli, 2008). This could enhance the transport and deposition of persistent contaminants in Antarctica (Xue et al., 2016). As already mentioned, the present chemical status of surface water in the Antarctic region is the effect of contemporary transport of pollutants, as well as the release of previously accumulated contaminants from glaciers and permafrost thawing (Herbert et al., 2006; Curtosi et al., 2007; Martins et al., 2010; Xue et al., 2016). It is assumed (Bengtson Nash, 2011) that Persistent Organic Pollutants (POPs) contained in permafrost may have their source in anthropogenic activities since the mid-1900s. Because of their toxicity, extreme persistence and bioaccumulation capacity, this compounds spread, what have resulted in contamination of Antarctic environment. Some of the pollutants stored in permafrost can also come from natural sources, as described in detail in the Subsections 3.1, 3.2 and 3.3 of this work. Climate change can also cause the intensification of the rate of glacier ablation and melt, resulting in higher concentrations of organic compounds from atmospheric deposition accumulated in meltwater, and then in glacier-associated persistent pollutants accumulated on the meltwater surface after the ice retreats or melts. Moreover, increased rain and thawing processes caused by global warming could cause a significant soil-associated mobilisation of pollution, which could in turn have unpredictable knock-on effects on biota (Curtosi et al., 2007). Processes of contamination transport within abiotic media are presented in Fig. 2.

Based on literature data (Bargagli, 2008; Corsolini, 2009; Szopińska et al., 2017; Bengtson Nash, 2011), two main groups of contaminants can be distinguished which may be stored and/or remobilised from permafrost, namely persistent organic pollution (POPs) and heavy metals.

POPs are toxic compounds produced by the industry and released to the environment through antropogenic activities. They are resistant to degradation, so they can accumulate in the environment over long periods of time in solid, liquid, or gas-phase reservoirs from which they pose risks to ecosystems and human health. Global contamination with POPs of all environmental matrices is caused by their extreme persistence and effective environmental dispersal mechanisms (Bengtson Nash, 2011).These contaminants include chemicals such as polychlorinated biphenyls (PCBs), pesticides, polycyclic aromatic hydrocarbons (PAHs), and unintentionally produced chemicals (such as dioxins and furans) (Bengtson Nash, 2011). The accumulation of semi-volatile chemicals in cold environments is caused by thermodynamic forcing by temperature gradients (Bengtson Nash, 2011; Ma et al., 2016). The authors also concluded that the long half-lives of these chemicals facilitate repeated cycles of volatilisation and deposition, which results in movement of semi-volatile chemicals away from temperate and tropical source regions towards colder climates. Bengtson Nash (2011) and Ma et al. (2016) point out that these compounds may be subject to “cold-trapping” in polar areas or at an altitude where colder temperatures further prolong their persistence.

Metals of anthropogenic origin, predominant in various components of the Antarctic environment are as follows: Cr, Ni, Cu, Zn, Pb, Cd (Chaparro et al., 2007). Hg is also noteworthy, not because of high concentrations in the environment, but because of its high toxicity (de Ferro et al., 2014). According to research by Lu et al. (2012), the average concentration of mercury in soil sampled from Fildes Peninsula is 0.0221 ng/g. Metals may affect biological processes positively or negatively, depending on their concentration. Trace elements in soils originate from natural and anthropogenic sources. The load of metals in the soil depends on the type of metal and soil, as well as on the subsequent accumulation of the metal in other elements of the environment. It has been proven that excessive levels of metal pollution in the environment may not only have negative effects on the soil's fertility, but also cause ecological and human health risk (Robinson et al., 2005). In Antarctica, sediments and soils are a major reservoir for metals. Therefore, they are an excellent source of information about the load of metal pollution over the years. Some sediments can also act as a source of contaminants (Santos et al., 2007). Antarctica plays a significant role in the determination of global contamination levels and trends. Natural baseline levels of metals in the Antarctic environment are a gauge of changes in their global concentration (Lu et al., 2012).

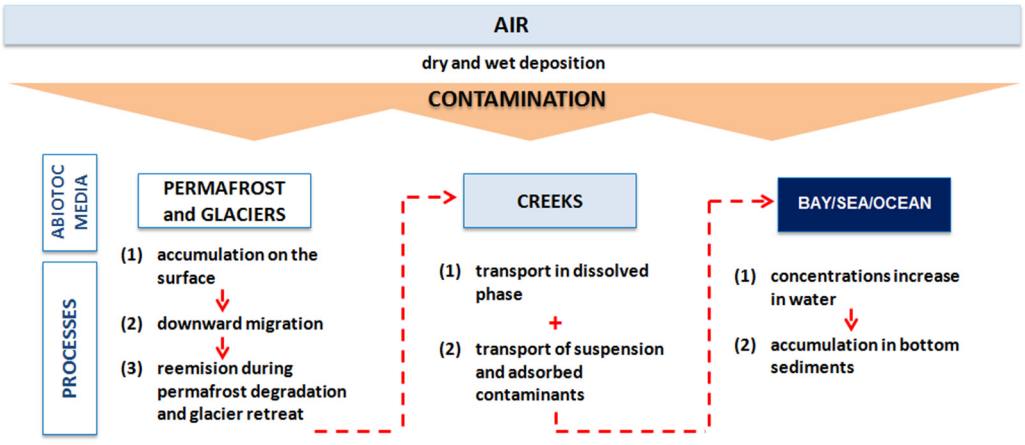


Fig. 2. Environmental fate of contamination delivered to Antarctica via long-range atmospheric transport (LRAT) in abiotic components.

3.1. Pesticides and trace PCBs

Polychlorinated biphenyls (PCBs) belong to the group of organochlorine compounds. The emissions of PCBs and pesticides are successful curtailing, although the chemicals still pervade global ecosystems. These compounds are present also in Antarctic. They generally come from LRAT via precipitation and cold condensation. Moreover, snow also has influence on the deposition and the fate of PCBs in cold environments (Klánová et al., 2008).

Contemporary research (e.g. Cabrerizo et al., 2013; Bengtson Nash, 2011; Klánová et al., 2008; Ma et al., 2011) suggests that the existence of many sources of PCBs and pesticides contamination in the Antarctic areas. First of all, polar regions receive the chemicals through atmospheric transport and deposition, and are accumulated in soils, ice, and waters. Nonetheless, contemporary research (Geisz et al., 2008; Ma et al., 2011; Cabrerizo et al., 2013) on polar regions has shown evidence that historical burdens of PCBs and pesticides are currently being remobilised from retreating permafrost cover in Antarctica. This remobilisation may be enhanced under climate change and result in an increase in their availability for exchange with the atmosphere, whereby the ecosystem's exposure to previously immobilised PCBs and pesticides is increasing (Noyes et al., 2009; Cabrerizo et al., 2013). Moreover, due to the intensifying effect of climate warming, vapour pressure increases, resulting in an alteration of the thermodynamic equilibria for partitioning of PCBs among various environmental media (Ma et al., 2016) and e.g. their distribution into aquatic environment.

According to Klánová et al. (2008), whose research included the James Ross Island area, soil concentrations of PCB ranged between 0.510 and 1.82 ng/g. Cabrerizo et al. (2012) studied soils from the surface layer and 5 cm under its surface from the Livingston and Deception Islands. According to the authors, PCB concentrations were between 0.005 and 0.320 ng/g. Studies covering soils from the eastern part of Antarctica (Borghini et al., 2005; Negoita et al., 2003) suggest that levels of PCB contamination were similar to those in West Antarctica, as presented in Table 2. Cabrerizo et al. (2012) showed that the concentrations of pesticides in soils from the western part of Antarctica are significantly lower compared to PCB concentrations. According to the authors, hexachlorobenzene (HCB) concentrations fluctuated in the range of <LOQ-0.07 ng/g, while concentrations of p,p′-Dichlorodiphenyldichloroethylene (p,p′-DDE) from loq to 0.20 ng/g. Borghini et al. (2005) and Negoita et al. (2003) stated the presence of HCB and p,p′-DDE in soils from East Antarctic in concentrations: 0.02–25 ng/g, and 0.03–4 ng/g, respectively.

Chemicals present in soil after remobilisation may pass into water, the food web, and then top aquatic predators. Aquatic food webs are particularly prone to the biomagnification of PCBs (Ma et al., 2016). PCBs and organochlorinated pesticides (OCPs) bioaccumulate through food webs and reach significant levels in top predators because of their lipophilicity (Klánová et al., 2008). Furthermore, PCBs were among the earliest groups of man-made chemicals to be encountered in food webs. These compounds are the most widespread in the environment and biota, compared with others POPs (Baert et al., 2013). It

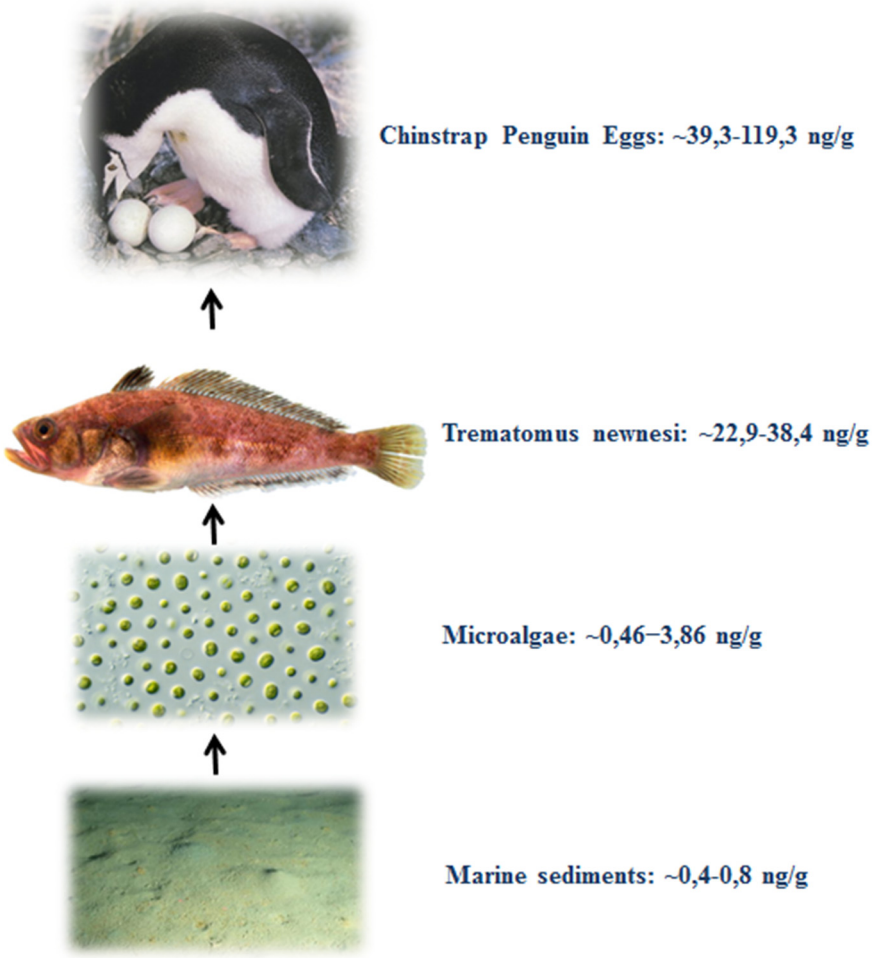


Fig. 3. Schematic view of ΣPCB bioaccumulation and bioamplification in Antarctica's marine food. Sources of PCBs concentrations are microalgae (Cabrerizo et al., 2012); marine sediments (Klánová et al., 2008); *Trematomus newnesi* (Lana et al., 2014); and Chinstrap Penguin Eggs (Mello et al., 2016). Pictures accessed from the websites: http://fishphylogenetics.blogspot.com/2012/09/an-adaptive-radiation-on-ice.html, http://hmsc.oregonstate.edu/research-labs/reimers-lab/current-research, http://www.animalspot.net/chinstrap-penguin.html, https://en.wikipedia.org/wiki/Microalgae.

is due to their durability in the environment and persistence to common (bio)-degradation pathways (Baert et al., 2013). In the Antarctic marine food web, biomagnification proceeds e.g. from microalgae to fish (*Trematomus newnesi*), with the higher trophic levels contributing to the traditional diet of Chinstrap Penguin (Fig. 3), therefore posing risk (Mello et al., 2016). Indirect connections exist between climate change and PCBs contamination to wildlife. An example is migration of marine species caused by climate warming and loss of ice cover (Cabrerizo et al., 2012; Lana et al., 2014; Mello et al., 2016). The effect may be altered exposure to PCBs on account of eating organisms containing high concentrations of PCBs, even if the migratory transport of the chemicals is small relative to quantities transported by other ways (Cabrerizo et al., 2012; Klánová et al., 2008). The altered climate of Antarctic also entails certain changes in the type of food consumed. Studies on levels of concentration in the tissues of birds inhabiting Antarctic proved that transequatorial migrant species such as skuas (*Chataracta* spp.) have higher PCBs burdens than penguins (*Pygoscelis* sp.). Based on the above, migratory seabirds, e.g. south polar skua, can affect a vehicle transport of chemicals. The result is contaminants of PCBs and pesticides from the northern regions to Antarctica (Mello et al., 2016).

3.2. Polycyclic aromatic hydrocarbons and alkanes

Any human activity in Antarctica, even limited to conducting scientific research, carries with it environmental risks associated with the use of fossil fuels. Scientific operations and the related logistic support require using them as an energy source for heating and lighting at the research stations, as well as a fuel for research boats, terrestrial vehicles, and re-supply vessels (Curtosi et al., 2007; Martins et al., 2010). In a year, fuel consumption by research stations amounts to approximately 90 million l 75% of which is diesel fuel (Martins et al., 2004). Increasing tourist activities in Antarctica and fisheries may also cause a risk for direct releases of hydrocarbons to the environment (Curtosi et al., 2007). In order to determine the record of human activities and remote contamination transported to the Antarctica, it is necessary to apply appropriate indicators such as concentrations of specific groups of polycyclic aromatic hydrocarbons (PAHs), alkanes, and even spheroidal carbonaceous particles (Martins et al., 2010). These compounds are transported to surface sediments by binding with suspended particulate matter in the water column (Martins et al., 2010). They are rarely found as products of biosynthesis. These compounds reach the marine environment mainly by human activity, and due to their properties they have a toxic effect on the environment (Martins et al., 2004).

Although Antarctica is considered as one of the most pristine areas of the world (Pongpiachan et al., 2017), several previous works (Martins et al., 2004; Cripps and Shears, 1997; Kennicutt et al., 1991) reported sporadic hydrocarbons pollution events (e.g. oil splits) in various components of this environment. Moreover, PAHs are produced in the process of fossil fuel combustion, especially during the process of its incomplete combustion. Fossil fuels are the most widespread source of energy in the southern hemisphere. PAHs generated in combustion processes enter the Antarctic environment, disturbing the functioning of ecosystems, as detailed in Chapter 4. Due to this, these compounds are one of the most important anthropogenic contaminants of the Antarctic environment (Martins et al., 2004; Martins et al., 2010). The compounds can also be formed during the combustion of wood and other organic materials (Curtosi et al., 2007). Anthropogenic sources of PAHs in the marine environment and soils of Antarctic are sewage discharge, vehicular emissions, and spillages of petroleum and its by-products containing complex mixtures of petrogenic PAHs (Martins et al., 2004; Martins et al., 2010). Although these external sources of hydrocarbons do not originate from the territory of Antarctica but at a considerable distance from this area, hydrocarbons are transferred to the Antarctic environment on account of LRAT (Martins et al., 2004). Little information about the natural sources of PAHs in the Antarctic environment has been found in the literature. Based on the work of Cabrerizo et al. (2012), one can assume that the significant source of these compounds may be the eruptions of the volcanos e.g. on Deception Island. In the case of n-alkanes, in addition to anthropogenic sources such as diesel oil degradation, there are also ones of biogenic origin, identified in many species of marine organisms. N-alkanes from biogenic sources are variable depending on the organisms present in a given study area (Martins et al., 2004). All hydrocarbon sources mentioned above (natural or anthropogenic) originate from local activities in Antarctica and therefore they can be classified as so-called in situ sources.

Some studies (Martins et al., 2004; Cripps and Shears, 1997; Kennicutt et al., 1991) on hydrocarbon contaminants discuss past incidents of oil spills in Antarctica which have caused severe localised effects on the fauna and flora, e.g. reduction of the survival of species and ecosystems (Cripps and Shears, 1997). It was also evidenced that such effects were of short-term character, and the recovery was rapid (Martins et al., 2004). Cripps and Shears (1997) showed that a diesel spill at Faraday Research Station that occurred on 2 March 1992 caused immediate toxic effect in the intertidal zone. However, because fuel dispersed quickly, as a result of evaporation, solution, and dispersal, the best strategy for small coastal fuel spills is initial cleaning followed by leaving the rest of the fuel to natural degradation processes.

Anderson et al. (1978) described the process of a slow sieving in permafrost, which happens because of repetitive cycles of freezing and thawing. Authors stated that during this process, small particles of soil migrate from surface to depth. In research of Krauss and Wilcke (2002), it was proved that PAHs are most of all adsorbed to the smallest particles. Additionally, Biggar et al. (1998) and McCarthy et al. (2004) hydrocarbon migration mechanisms are based on the gravity drainage through interconnected air voids in permafrost and in a minor extent the diffusion of this compounds in liquid water in soil, because permafrost is a barrier to water flow.

Cabrerizo et al. (2012) found the presence of PAHs on the Deception Island, Livingstone Island near Juan Carlos I Station, and Byers Peninsula (an Antarctic Specially Protected Area) in soils, mosses, lichens, algae, and some local plants. Researched by Curtosi et al. (2007) focused on soils from the vicinity of the Jubany Station and sediments from Potter Cove. The soil was taken from various depths. In the environmental samples, 25 compounds from the PAHs group were determined. Fourteen of the compounds were found in soils and six in marine sediments. Pongpiachan et al. (2017) also studied concentrations of PAHs in soil samples collected near the Great Wall Station (Chinese research station) located on the Fildes Peninsula on the King George Island. Martins et al. (2004), in addition to determining the concentration of PAHs, also confirmed the presence of aliphatic hydrocarbons in marine surface sediments around the Brazilian station in the Admiralty Bay. Bícego et al. (2009) studied concentrations of PAHs and hydrocarbons in water and sediments from the Admiralty Bay near research stations on the King George Island operated by Brazil, Poland, Peru, the United States of America, and Ecuador. The authors monitored the concentration of the compounds for 15 years. Table 1 presents results of PAHs content in soil from East and West Antarctic regions. The majority of the studies were performed in the South Shetland Archipelago region. There and other study results from West Antarctica are presented in Table 1. Based on this analysis it was found that levels of PAHs were variable in time and space. Since 2004, for the following 3 years, the minimum values of these compounds in western Antarctica have generally remained at the same level. A disturbing increase in the maximum concentration of PAHs occurred, however, in the years 2004–2009 in areas near the Antarctic research stations on the Antarctic Peninsula. The comparison of concentrations of PAH from 1999 and 2005 from eastern Antarctica shows a decrease in the level of soil pollution with these chemical compounds, both in terms of minimum and maximum values. From 2004 to 2009 in western Antarctica, a rapid increase in maximum concentration occurred from 45.0 to 3718 ng/g. Curtosi et al. (2007) concluded that rapid drainage of porous soils developed as a result of rainfall and melting snow and ice during summer could cause a

Table 1
PAHs concentrations in soils [ng/g dry weight].

Sampling area/Antarctic region	Year of research	Minimum value of ΣPAHs	Maximum value of ΣPAHs	References
Scott Base (Ross Island)/East Antarctic	1999	41	8105	Aislabie et al., 1999
Jubany Station (King George Island, South Shetland Islands)/West Antarctic	2004	11	45	Curtosi et al., 2007
Jubany Station (King George Island, South Shetland Islands)/West Antarctic	2005	11	588	Curtosi et al., 2007
Scott Base (Ross Island)/East Antarctic	2005	34.9	171	Klánová et al., 2008
Jubany Station (King George Island, South Shetland Islands)/West Antarctic	2007	10	1182	Curtosi et al., 2007
Juan Carlos I (Livingston Island, South Shetland Islands)/West Antarctic	2009	0.59	3718	Cabrerizo et al., 2012
Great Wall Station (King George Island, South Shetland Islands)/West Antarctic	2014	1.59	4.83	Pongpiachan et al., 2017

considerable inter-annual change in PAH concentrations in soils. They also linked high concentrations of these compounds to local sources of pollution such as accidental diesel spillage and low-temperature combustion of organic materials. Cabrerizo et al. (2012) showed that the mean concentrations of PAH in soil samples are in the range of 0.59–25.5 ng/g dw. They also stated that the exceptionally high PAHs concentration (3718 ng/g dw) detected in one sample is probably related to the fact that the soil samples were collected in the area where fossil fuel is usually stored, which might suggest accidental spillages. Moreover, Curtosi et al. (2007) pointed out that the active layer/permafrost transition zone showed the highest level of PAHs, and permafrost was revealed to be a low-permeability barrier to downward migration of these compounds. The thawing of the upper layer of permafrost, however, would have deep consequences in the transport and fate of the PAHs spilled on Antarctic soils, and would result in an increased flow of PAHs to coastal marine environments with unpredictable ecological consequences. In water, organic compounds such as PAHs and n-alkanes can be easily transported and accumulated in marine (Xue et al., 2016) and lake (Yao et al., 2016) sediments.

The presence of PAHs in such a pristine environment is even visible in penguins (Montone et al., 2016). Montone et al. (2016) have investigated the presence of PAHs in the main three species of penguins: the Gentoo (*Pygoscelis papua*); the Chinstrap (*Pygoscelis antarcticus*), and the Adelie (*Pygoscelis adealiae*) which constitute 95% of the biomass of breeding communities in this area (Sander et al., 2005). The levels of concentration in the fat are up to 238.7 ng g^{-1} wet weight. This evidences that PAHs, while moderately persistent in the environment, can be bio-accumulated. This phenomenon is also observed in fish fat tissues, e.g. in rock cod fish (*Trematomus bernacchii*) – 1520–1840 ng g^{-1} lipid wt (Hale et al., 2008). PAHs in penguins were dominated by two- and three-aromatic-ring compounds (Montone et al., 2016).

The literature provides no information on PAH concentrations after 2014. However, due to the increase in human activity in the regions of Antarctica, monitoring the level of concentration of these compounds can help improve and enhance legal acts protecting the environment of Antarctica.

3.3. Heavy metals and other elements

Heavy metals are a natural part of the Earth's crust. Based on the results of Lu et al. (2012); Carrasco and Préndez (1991); Zhao et al. (1989), Santos et al. (2005), Crockett (1998), it can be concluded that the dominant trace metals in the Antarctic environment are Al, Ca, Cd, Cr, Cu. These elements can get into the Antarctic environment via long-distance atmospheric transport and global circulation (Lu et al., 2012), and as a result of human activity in the vicinity of polar stations. Some of them (e.g. Al, Cu) can be considered to be of natural origin (Szopińska et al., 2018). Research on soil samples (Martins et al., 2002; Alam and Sadiq, 1993; Tin et al., 2009) has shown the relationship between the presence of several metals e.g. V, Ni, Zn, Cu, Cr, Pb, Ba with petroleum contamination. Potential sources of contamination with Pb and Cu include paints used for painting the internal and external surfaces of building walls (Webster et al., 2003). Point sources of Pb, Zn, and Cu in soils can be used batteries and rubbish resulting from activities in McMurdo Sound region (Santos et al., 2005). The main source of Pb in the Antarctic environment is fuel combustion. Hong et al., 1998 also stated that the source of Pb transported from areas distant from Antarctic is industrial activity and fuel consumption in large urban centers in South America. Several studies (Santos et al., 2005; Abakumov et al., 2017; Kennicutt et al., 1995; Lenihan, 1992) showed that concentrations of metals in sediments around the sewage outfall were higher than in sediments from areas far from the station, so another important source of metals is sewage. Not all research stations can use wastewater treatment plants. An increased concentration of trace elements, and particularly mercury, was observed in soils from the vicinity of Antarctic research stations that discharge untreated wastewater directly into the environment (Abakumov et al., 2017). Land relief has an effect on retention of these elements in the soil. On the other hand, anthropogenic input of organic matter to sediments favours sulfide formation, causing reduction of metal bioavailability, and consequently reducing adverse effects on local biota (Santos et al., 2005).

Numerous studies on the King George Island (e.g. Lu et al., 2012; Santos et al., 2005; Abakumov et al., 2017) proved that, as a result of human activity, large loads of elements are introduced into the Antarctic environment. Anthropogenic activity significantly affects the concentration levels of various elements in the environment, and makes it difficult to assess, whether the metals originate from natural or anthropogenic sources. Sediments and soils are major reservoirs for metals. They act as indicators of the quality of the environment (Santos et al., 2005). On the other hand, research by Szopińska et al. (2018) and Nędzarek et al. (2014) shows that the Arctowski Station (Polish Antarctic Station, King George Island) does not cause a significant increase in metal specific concentration (e.g. Pb). The studies evidenced that the recorded increased concentrations of trace elements may be associated with natural processes, and not necessarily with anthropogenic pollution such as researchers' activities. According to Lu et al. (2012), Nędzarek et al. (2014), by an equilibrium is possible to maintain metal values in Antarctic soils on baseline levels. The authors also concluded that this is caused by physical, e.g. mechanical erosion (Szopińska et al., 2018; Anderson et al., 2000), chemical e.g. geochemical weathering, of volcanic rocks (Nędzarek et al., 2014), as well as biological processes (Malandrino et al., 2009) occurring in the soil environment and interactions between them.

Another natural source of metals in Antarctic environment is birds, which have been determined to play a significant role in the alteration of chemical composition of soils and sediments. Such conclusions were drawn from research on the content of trace metals in guano. Some vascular plants, e.g. Antarctic hair grass (*Deschampsia Antarctica*), can concentrate some trace elements. These plants can be collected by birds, transported, and used to build nests. Based on the aforementioned circumstances, trace elements were found to be accumulated in ornithogenic soils (Abakumov et al., 2017).

According to Bockheim and Hall (2002), the process of soil formation in Antarctic is evidently slower in comparison to other continental environments. According to the literature, soil development as well as chemical and mineralogical changes in Antarctic are inhibited by factors

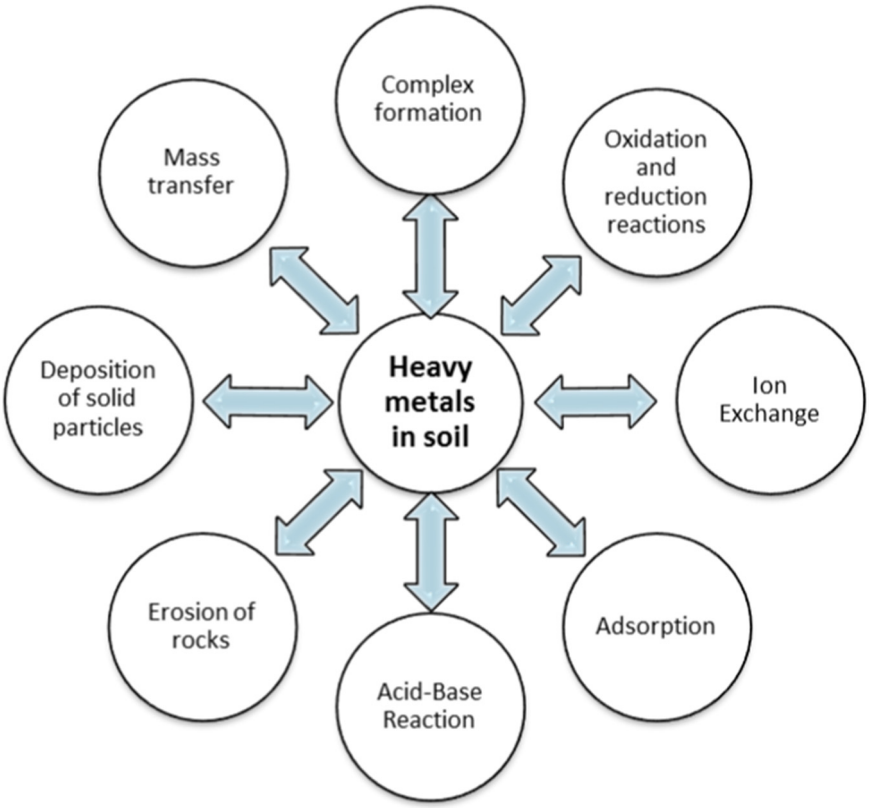


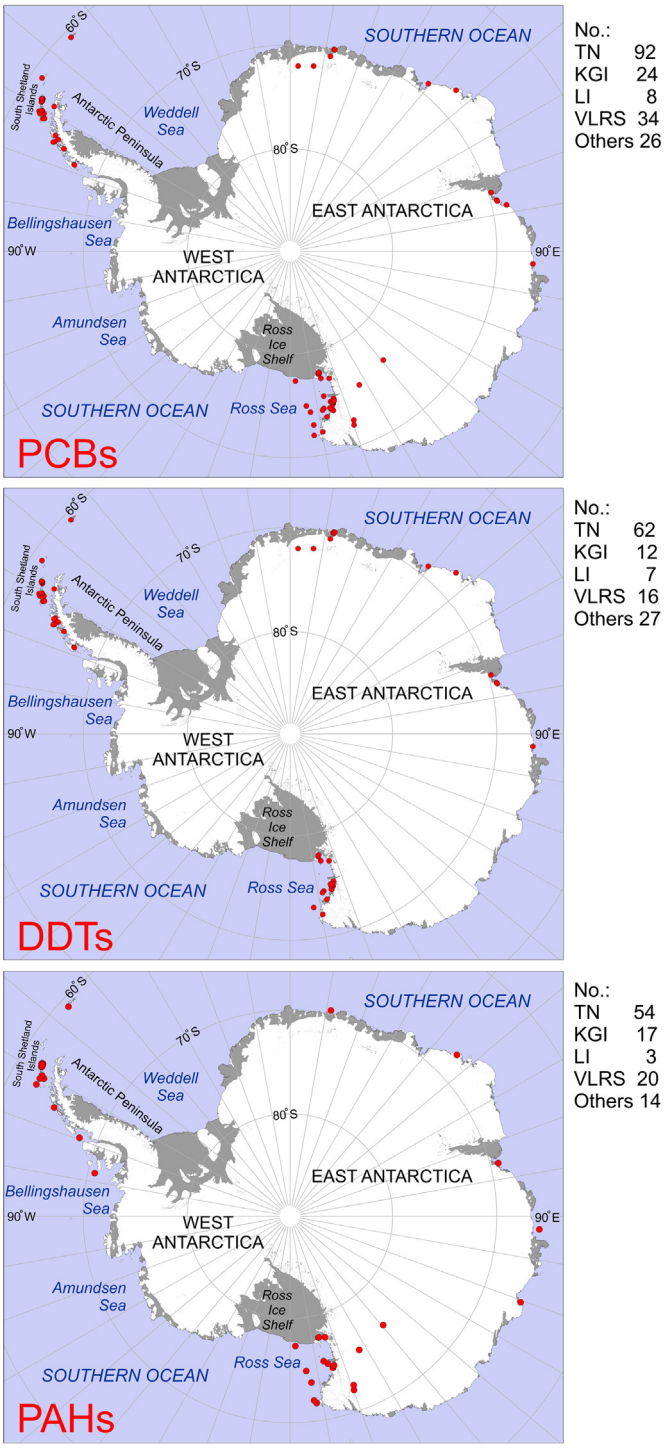
Fig. 4. A diagram presenting processes by which heavy metals pass to the soil (McLean and Bledsoe, 1992; Robinson et al., 2005; Nagare et al., 2012).

such as low temperature and limited quantity of liquid water (Navas et al., 2008; Simas et al., 2006; Vennum and Nejedly, 1990), characteristic of this area. As shown in Fig. 4, there are some further processes, including ligand exchange, adsorption, precipitation, and acid-base reactions, which have an effect on the distribution of dissolved and particulate metals in soils. Research by Basta and McGowen (2004) and White et al. (2012) shows that the mobilisation of some trace metals in soil (e.g. As or Sb) is caused by changes in the pH or redox conditions. For example, accumulation of birds and penguins guano promotes soil acidification (Poggere et al., 2017). Although pH of fresh guano is alkaline, it is quickly acidified up to a pH value of 4.0 as a result of sulfuric and nitric acid formation caused by its biological stabilisation on the ground (Tatur, 1989). As a result of guano accumulation, the chemical weathering process in the clay fraction becomes more intense. This in turn increases the intensity of short-range order phases (Poggere et al., 2016). Their characteristic feature is highly specific surface, where groups that are reactive e.g. silanol (eSiOH), aluminol (eAlOH), ferrol (eFeOH) are present (Poggere et al., 2017; Wada, 1989). These reactive groups present in the Antarctic environment have been evidenced to cause an increase in the intensity of adsorption of heavy metals (Mendonça et al., 2013). In addition to soil acidification in the Antarctic environment, guano also causes leaching of exchangeable bases, and transformation of primary minerals. According to Mendonça et al. (2013), metals (e.g. Fe, Al) in the form of ions or amorphous metals are released into the soil environment, and then bind to phosphorus compounds derived from ornithogenic activity forming compounds such as leucophosphite [$KFe^{3+}{}_2(PO_4)_2(OH)\cdot 2H_2O$] and metavariscite [$AlPO_4\cdot 2H_2O$].

Moreover, a relationship has been observed between the content of total organic carbon (TOC) in soil samples and the concentration of some heavy metals, e.g. Hg (de Ferro et al., 2014). The chemical processes of metals in Antarctic soils are governed by processes such as adsorption on various solid phases and reactions with organic matter. As a result of the latter, complexes and metal chelates are formed, quite persistent in the environment, and precipitation of compounds, generally stable or moderately soluble, occurs (Bradl, 2004). Poggere et al. (2017) have recently shown that in permafrost-affected areas of Antarctica, erosion of rocks plays a significant role in the transport of trace metals. For example, as a result of pyrite oxidation (FeS), a sulphate is formed and minerals such as jarosite [$KFe^{3+}{}_3(SO_4)_2(OH)_6$] and natrojarosite [$NaFe^{3+}{}_3(SO_4)_2(OH)_6$] precipitate (Simas et al., 2006).

According to research from permafrost areas (e.g. Panin and Kazantsev, 1986; Ostroumov et al., 1998; Ostroumov et al., 2001; Streletskii et al., 2003), the transport of metal ions in long-term permafrost in the Antarctic is closely related to the movement of water. It is possible through water films adsorbed by soil particles. Water films can then transport these chemical entities. In many scientific studies (e.g. Cary and Mayland, 1972; Chamberlain, 1983; Henry, 1988; Marion, 1995) regarding the redistribution of soluble components in permafrost-affected soils, a dependence was observed between freeze-thaw processes and selected chemical elements in soils. Water transport in freezing soils particularly takes place through the capillary phenomena. Cryogenic suction occurs through a pressure deficit or negative pressure. In Antarctic soils affected by permafrost, the temperature gradient does not change despite seasonal changes of its direction in autumn and spring (Antcibor, 2014). A decrease in heat input to the surface soil horizons in autumn causes downward freezing from the top soils, and upward freezing of the active layer from the permafrost table. The migration process of water molecules in the soil profile depends on their movement from the unfrozen side to the frozen side along with water films adsorbed to soil particles. If the soil begins to freeze, water that is least attached to soil particles freezes first. Then in the soil pore spaces, ice crystals are formed. Many studied (e.g. Illuminati et al., 2016; de Oliveira et al., 2017; Vodopivez et al., 2015; Husmann et al., 2012) discussed the occurrence of heavy metals in the tissues of living organisms. According to Goutte et al. (2015), the concentrations of trace elements increase along with higher trophic level

of organisms as a result of bioaccumulation and bioamplification processes within trophic webs occurring in Antarctica (Atwell et al., 1998; Morel et al., 1998). Moreover, that level of exposure to trace metals was found to be dependent on the foraging habitat (Goutte et al., 2015). For example, fish species inhabiting the benthic boundary layer will have a higher level of Hg in the tissues than those foraging in the water column and underneath sea ice (Fitzgerald et al., 2007). Seabirds were evidenced to be excellent bioindicators of Hg pollution (Burger and Gochfeld, 2004), because feathers are the main route of Hg excretion in birds (Monteiro and Furness, 1995). Research by Carravieri et al. (2013) showed that in long-lived animals, Hg can bioaccumulate in their tissues over their whole life span. The mechanism of metal accumulation was also observed in the tissues of lichens (Guerra et al., 2011). The authors concluded that some chemicals naturally occurring in lichens, e.g. usnic, pulvinic, and rhizocorpic acids, can promote the formation of stable complexes with metals. Grotti et al. (2008) showed that as a result of low temperature of Antarctic water, specific ways of feeding, and longevity, the bioaccumulation of metals in Antarctic organisms may be more intense than in other environments.



4. Possible environmental consequences of the presence of contaminants released from permafrost or the cryosphere

Recent years have seen higher temperatures (Chapman and Walsh, 2006; Turner et al., 2005) and changing stocks of soil organic matter (SOM) on the Antarctic Peninsula (Vaughan et al., 2003; Hill et al., 2011; Cabrerizo et al., 2012). This is probably related to a number of factors such as changes in the soil metabolism, changes in vegetation cover, or increase in impact from human settlements. A significant change has been observed in the extent of terrestrial biota habitats in the Antarctic Peninsula (Cabrerizo et al., 2013; Hill et al., 2011). This is exemplified by growth rates of lichen *Usnea Antarctica*. On the Livingstone Island, its annual growth rate in length of 2 mm per year with an increase in the lichen diameter from 50 in 1991 to 72 mm in 2002 was observed. This is probably correlated with rising temperatures and glacier retreat in the Antarctic (Cabrerizo et al., 2012). Changes in vegetation occurring on the Antarctic Peninsula can be a source of changes in C and N circulation. Cabrerizo et al. (2013) concluded that it can potentially exert a significant influence on POPs circulation through the changing SOM pools. In the context of combined climatic and biogeochemical factors, global change involving different temperatures and organic matter stocks will affect the revolatilisation and reservoirs of POPs (Cabrerizo et al., 2013).

The determination of the exact impact of POPs on Antarctic species and systems, or making forecasts for the future is not yet possible due to the still insufficient number of studies on the Antarctic environment in this aspect. The map of selected POPs (Fig. 5) shows that investigations were focused mainly on the selected parts of Antarctica (South Shetland Islands, Antarctic Peninsula, Victoria Land and Scott Sea), less often they were conducted in the central part of the continent (Vecchiato et al., 2015). However, it is very likely that POPs may be present in the whole Antarctica. Toxic responses to these chemicals, however, have been widely reported in research based on experiments with primarily temperate species under standard test conditions (Bengtson Nash, 2011). It provides the basis for risk assessment for

Fig. 5. Location of research areas in Antarctica, where selected POPs have been determined in biotic and abiotic samples. Abbreviation: TN – total number of researched points, KGI – number of researched points in King George Island, LI – number of researched points in Livingstone Island, VLRS – number of researched points in Victoria Land and Ross Sea, Others – total number of other researched points (prepared based on results obtained by Platt and Mackie, 1980; Subramanian et al., 1983; Bacci et al., 1986; Risebrough et al., 1990; Focardi et al., 1991; Larsson et al., 1992; Caricchia et al., 1995; Kennicutt et al., 1995; Bicego et al., 1996; Fuoco et al., 1996; Inomata et al., 1996; Sen Gupta et al., 1996; Court et al., 1997; Kallenborn et al., 1998; Aislabie et al., 1999; Mazzera et al., 1999; Montone et al., 2001; Corsolini et al., 2002a; Corsolini et al., 2002b; Crockett and White, 2003; Negoita et al., 2003; Montone et al., 2003; Weber and Goerke, 2003; Borghini et al., 2005; Gambaro et al., 2005; Montone et al., 2005; Bustnes et al., 2006; Corsolini et al., 2006; Kim et al., 2006; Negri et al., 2006; Nemirovskaya, 2006; Corsolini et al., 2007; Curtosi et al., 2007; Krahn et al., 2007; Borghesi et al., 2008; Choi et al., 2008; Cincinelli et al., 2008; Geisz et al., 2008; Klánová et al., 2008; Curtosi et al., 2009; Fuoco et al., 2009; Schiavone et al., 2009a; Schiavone et al., 2009b; Stortini et al., 2009; Taniguchi et al., 2009; Yogui and Sericano, 2009; Cipro et al., 2010; Martins et al., 2010; Park et al., 2010; Corsolini et al., 2011; Van den Brink et al., 2011; Cabrerizo et al., 2012; Fuoco et al., 2012; Li et al., 2012; Trumble et al., 2012; Cabrerizo et al., 2013; Kallenborn et al., 2013; Zhang et al., 2013; Cabrerizo et al., 2014; Lana et al., 2014; Dauner et al., 2015; Jara-Carrasco et al., 2015; Vecchiato et al., 2015; Alexander et al., 2017; Mello et al., 2016; Pongpiachan et al., 2017; the basic maps of Antarctica have been obtained from British Antarctic Survey Geodata Portal, http://add.antarctica.ac.uk/repository/).

Table 2
Examples of negative effects of selected pollutants on living organisms occurring in the Antarctic area.

Contaminants	Species	Observed biological changes	Ref
PAHs	Fish *Notothenia coriiceps*	- Carcinogenic effects on fish; - Damage to liver cells	Curtosi et al., 2009
Hydrocarbons (PAHs, alkanes)	Antarctic sea urchins (*Sterechinus neumayeri*)	- Increased toxic effects immediately following hatching	Alexander et al., 2017
PCBs, HCB, DDT, α-endosulfan, β-endosulfan	Chinstrap penguin (*Pygoscelis antarctica*)	- Decreased reproductive success; - Increased risk of parasitism; - Greater wing asymmetry; - Immunohematological disorders;	Jara-Carrasco et al., 2015
Hg, Pb	Nacella polaris (*Nacella concinna*)	- Disorders of the functioning of gills and muscles; - Inhibitors of arginase activity	de Oliveira et al., 2017
Hg, Cd, Pb	Bald notothen (*Pagothenia borchgrevinki*); Antarctic silverfish (*Pleuragramma antarcticum*); *Notothenia coriiceps*; Emerald rockcod (*Trematomus bernacchii*); *Trematomus hansoni*; *Trematomus newnesi*, *Trematomus pennellii*	- Endocrine disruption; - DNA damage; - Immunotoxicity; - Reprotoxicity	Goutte et al., 2015

high latitude environments. Polar environments have evolved a "boom and bust" ecology governed by seasonal irradiation and primary production (Bengtson Nash, 2011). Moreover, pollutants present in Antarctica may have a number of adverse effects on living organisms, as shown in Table 2. In view of little exposure to POPs and other anthropogenic xenobiotics in the past, the Antarctic organisms probably have not developed detoxification mechanisms like their temperate and tropical counterparts. Sensitivity tests of Antarctic echinoid *Sterechinus neumayeri* on heavy metals showed that its sensitivity was comparable with that of its temperate and tropical counterparts, considering toxicity endpoints at equal exposure durations. Polar organisms, however, are characterised by gigantism as well as slow metabolism and development. Toxicity endpoints can be a good ecological indicator of toxicity comparison only in parallel comparable developmental stages (Bengtson Nash, 2011).

4.1. Pesticides and trace PCBs

Global warming could have a negative effect on the West Antarctic's environment, potentially becoming a net sink of POPs, including pesticides and PCBs (Cabrerizo et al., 2013). Moreover, due to the high storage capacity of soils, the amount of PCBs stored in soils would be up to 74 times higher than in the atmosphere (Cabrerizo et al., 2013). The appearance of relevant sorbing phases at each site (fugacity capacity) in soils of Antarctica can cause better uptake of POPs in Antarctic vegetation. Various factors, including the lipid content, and to a lesser extent age and growth rate, have influence on the accumulation of these compounds in vegetation. The literature provides no information on the age of Antarctic vegetation in the study area. Nonetheless, the organisms are assumed to have been present in the area for a long time, because their growth rate is limited to the environmental conditions which may affect POPs storage.

Mosses and lichens can accumulate and concentrate toxic substances even when POPs are present at low concentrations in the local environment (Cabrerizo et al., 2012). Table 3 shows the concentrations of selected POPs for Antarctic vegetation. POPs concentration values, including PCBs, hexachlorobenzene (HCB), and p,p′-dichlorodiphenyldichloroethylene (p,p′-DDE), determined in tissues of mosses and lichens from the eastern part of Antarctica, range from 0.2 to 34 ng/g dw. In contrast, concentrations of these compounds in mosses and lichens from the western part of Antarctica range from 0.002 to 40 ng/g dw. Microalgae, hair grass, pearl-wort, and green algae are also excellent bioindicators of air pollution of Antarctica (Park et al., 2010; Bacci et al., 1986; Negoita et al., 2003; Cabrerizo et al., 2012; Borghini et al., 2005; Focardi et al., 1991; Montone et al., 2001).

A compared with the range of concentrations of PCBs and pesticides in soils from western Antarctica, concentrations in Antarctic biota have a larger range of concentrations of these compounds (PCB: 0.005–3,86 ng/g dw; HCB: 0.002–2.16 ng/g dw; p,p′-DDE: 0.003–0.60 ng/g dw). In the case of samples from eastern Antarctica, PCB concentrations in Antarctic biota were significantly higher than in soils (soil: 0.005–0.32 ng/g dw; biota: 3.3–34 ng/g dw). HCB concentrations were higher in soils (0.02–25 ng/g dw) than in Antarctic biota

Table 3
Concentration of selected POPs in Antarctic biota.

Sample type	Sampling site/Antarctic sector	ΣPCBs (ng/g dw)	ΣHCB (ng/g dw)	p,p′-DDE (ng/g dw)	Ref
Lichens	King George Island/West Antarctica	0.005–0.04			Park et al., 2010
Lichens	Antarctic Peninsula/West Antarctica		0.32–2.16	0.10–0.60	Bacci et al., 1986
Lichens	Russian stations: Novolazarevskaya, Molodezhnaya, Stornes Peninsula, Progress, Druzhnaya IV and Mirny/East Antarctica	3.3	0.3	0.4	Negoita et al., 2003
Lichens	South Shetland Islands/West Antarctica	0.043–0.61	0.002–0.31	0.003–0.01	Cabrerizo et al., 2012
Mosses	Victoria Land/East Antarctica	23–34	0.85–1.90	1.10–7.90	Borghini et al., 2005
Mosses	Kay Island, Ross Sea/East Antarctica	5–16	0.30–0.80	0.20	Focardi et al., 1991
Mosses	Antarctic Peninsula/West Antarctica		0.30–0.68	0.17–0.53	Bacci et al., 1986
Mosses	South Shetland Islands/West Antarctica	0.04–0.76	0.021–0.12	0.005–0.04	Cabrerizo et al., 2012
Microalgae	King George Island/West Antarctica	0.46–3.86			Montone et al., 2001
Hair grass	South Shetland Islands/West Antarctica	0.39–2.40	0.080–0.20	0.061–0.09	Cabrerizo et al., 2012
Pearl-wort	South Shetland Islands/West Antarctica	0.31	0.04	0.04	Cabrerizo et al., 2012
Green algae	South Shetland Islands/West Antarctica	0.86	0.033	0.08	Cabrerizo et al., 2012
Penguin blood	Lenie Field Station, Admiralty Bay, King George Island/West Antarctica	3.4–9.8	2.7–6.7	4–8.2	Corsolini et al., 2007
Penguin blood	Livingston Island, Kopaitic Island, King George Island/West Antarctica	7.35–8.04	0.79–0.90		Jara-Carrasco et al., 2015
Eggs of seabirds	Admiralty Bay, King George Island/West Antarctica	44.31–1670	118–152		Mello et al., 2016
Tissues of fish	Potter Cove, King George Island/West Antarctica	11.1–99.0		4.59–20.6	Lana et al., 2014

(0.3–1.9 ng/g dw), while the level of p,p′-DDE in soil and Antarctic biota were higher. Some samples of mosses, however, were characterised by a higher content of these pesticides (soil: 0.03–4 ng/g dw; biota: 0.2–7.9 ng/g dw).

An additional factor increasing the risk of POPs accumulation in the tissues of Antarctic organisms are periodic shortages of food and low temperatures (Bengtson Nash, 2011). In conditions of food shortage, lipids are mobilised to satisfy it. This causes a load on contaminants, e.g. POPs contained in lipids. This phenomenon has previously been demonstrated in humans as well as wildlife. The highest vulnerability to the harmful effects of POPs is observed in animal species pushed to physiological extremes through shortage of food, reproduction, or migration, e.g. baleen whales and certain penguin species. It is caused by the re-mobilisation of POPs contained in the adipose tissue and therefore exposure of the body to the toxic effects of these compounds.

4.2. Polycyclic aromatic hydrocarbons and alkanes

Environmental risks regarding the accumulation of PAHs have increased in recent decades due to the growth of anthropogenic emissions from the southern hemisphere (Bargagli, 2008; Xue et al., 2016). Moreover, results showing the capacity for bioaccumulation of PAHs in living organisms, their toxicity, and mutagenity (Yang et al., 2015) demonstrate increased environmental burden of PAHs, particularly in reference to the sensitive Antarctic environment (Cabrerizo et al., 2012). The exposure of PAHs in the Antarctic environment constitutes a threat to Antarctic biota. Mosses are one of the primary components of terrestrial flora in this region. Because they have no root system, they are largely reliant for the nutrients supply on atmospheric deposition (Borghini et al., 2005). PAH accumulation in mosses (Cabrerizo et al., 2012; Colabuono et al., 2015) suggests that Antarctica may become an important sink in the global PAH cycle (Cabrerizo et al., 2012).

Furthermore, Pongpiachan et al. (2017) calculated the quantitative ecological risk assessment of inhabitants exposed to polycyclic aromatic hydrocarbons present in soil samples. The study was conducted on the King George Island, near the Great Wall station in January 2014. The environmental exposure to PAHs for humans in terms of cancer and non-cancer risks was found to be at an "acceptable level".

4.3. Heavy metals and other elements

An increase in human activities in Antarctica, particularly in the "hot spots" near research stations, may further threaten the purity status of the continent if proper precautions are not taken (Lu et al., 2012). At least until the 1990s, no adequate procedures of waste management existed there, leading to the deterioration of the metal pollution situation. As a result of accumulation of progressively adverse effects of different magnitude, the biological, physical, and landscape component of the Antarctic was affected (Chaparro et al., 2007). One of the most noticeable effects of human activity is the accumulation of the trace metals in soils and plant tissues. It has been proven (Amaro et al., 2016) that mercury accumulates more intensively in soils than in mosses. Moreover, the storage of waste causes the emission of chromium and nickel to the soil, where the accumulation of these metals takes place (Abakumov et al., 2017). It has been proved that in Arctic, trace metals are released from permafrost in larger quantities in the summer season, when air temperatures are higher than for the rest of the year (Robinson et al., 2005). Due to the presence of long-term permafrost in Antarctic, the same effect can be assumed to take place. Such a sharp increase in the trace metal load may pose a threat to the environment.

5. Conclusions

Due to prevailing extreme weather, Antarctica provides conditions favourable for permafrost occurrence. According to the available literature, soils of areas free from ice constitute a place of accumulation of heavy metals, PCBs, and PAHs. Due to the sensitivity of permafrost to climate change, the pollution of anthropogenic origin accumulated over the years may be released into the Antarctic environment under the variable conditions. In the context of climate change (depending on the part of Antarctic), either trapping of the compounds (places where cooling is observed/forecasted) or their release can occur (in places of observed/forecasted warming). Moreover, the cycles of accumulation and release of pollutants are also believed to be of seasonal character (winter-summer). Nonetheless, the greatest threat for the environment is posed by pollution reemission. Unfortunately, the literature still provides on information concerning the detailed description of the circulation of pollutants in the Antarctic environment, including the degree of effect of permafrost degradation on pollution remobilisation.

It can be concluded that climate change has become an integral component of research on POPs and heavy metals in Antarctica. These chemical compounds have a negative effect on living organisms occurring in Antarctica, and consequently disturb natural ecosystems in the area. In order to understand the anthropogenic processes and sources of contamination POPs and heavy metals better, their concentration in Antarctica should be constantly monitored. Considering the fact that chemical compounds described in the paper also have their natural sources, there is a need to create indicators of anthropogenic pollution. This would allow to distinguish which of the pollutants are related to human activity, learn about the mechanisms of their migration and limit their emission to the environment. The acquired knowledge can be used in the future for rapid response and environmental renewal in the event of ecological disasters, e.g. oil spills. It will permit limiting the negative impact of humans on the Antarctic environment (e.g. via applying enhanced environmentally friendly solutions), and therefore preserving the environment not only for Antarctic fauna and flora, but also for future generations.

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